~~Security Information~~
~~R E S T R I C T E D~~

CONFIDENTIAL

PRINCETON UNIVERSITY

DEPARTMENT OF AERONAUTICAL ENGINEERING

BEST AVAILABLE COPY

CONFIDENTIAL

~~Security Information~~
~~R E S T R I C T E D~~

54AA-25181

CONFIDENTIAL

OFFICE OF NAVAL RESEARCH
CONTRACT N6 onr-27015

MODEL STUDY OF HELICOPTER DYNAMIC STABILITY AND CONTROL

MODEL ROTOR TEST STAND

Aeronautical Engineering Department
Report No. 250
November, 1953

Prepared by: Robin Gray
ROBIN GRAY

Approved by: A. A. Nikolsky
A. A. NIKOLSKY

CONFIDENTIAL

Summary:

A description of a six-component model rotor test stand is presented in which strain gage beams are used to measure the forces and moments. A model helicopter having a single six-foot diameter, two-bladed teetering rotor was rigidly fixed to the stand and was tested in a hovering flight attitude at various collective blade pitch angles, rotor angular velocities, and cyclic blade pitch angles. The resulting steady state torques, thrusts, horizontal forces, and rotor flapping angles were measured to check the validity of the design. The results indicate that the rotor test stand data is accurate and repeatable.

Introduction:

The Forrestal Research Center, Princeton University, under the sponsorship and with the financial assistance of the Office of Naval Research is currently engaged in an investigation into the problems of helicopter stability and control. The method of attack, in general, has been the paralleling of a theoretical analysis with an experimental analysis of a suitable model. In experiments in which rotors were used, the rotors were initially subjected to a thorough static test analysis which required a rotor test stand. In the past, this need has been filled by a knife-edge type balance which was capable of measuring thrust and torque only.

The theoretical analysis of the dynamic stability of a model helicopter near hovering flight indicated that several of the stability derivatives could be determined from a static test analysis. This however required among other things the measurement of the transient horizontal force due to the displacement of the

tip path plane by a cyclic blade pitch angle. In as much as the determination of all the important stability derivatives from flight tests had proved difficult, it appeared that the problem could be alleviated somewhat by constructing a suitable rotor test stand and evaluating these several derivatives.

This report then, describes the design and instrumentation of the test stand and also includes the steady state test results from a model helicopter.

Description of Test Equipment:

The test components employed in this experimental research program included the rotor static test stand, a model helicopter with associated controls and instrumentation, and a completely enclosed test space. The model helicopter, its controls and instrumentation, and the test facility are described in reference 1. The rotor system is the same one used in reference 1 and has the following characteristics:

Rotor diameter, ft.	6
Number of blades	2
Solidity ratio	.0441
Blade section (no twist or taper)	NACA 0015
Airfoil section begins at 0.6 ft. radius	

A general view of the rotor test stand, the model helicopter and the test facility is illustrated in figure 1. The base of the test stand is a section of steel channel. The mast is made up of four sections, of which three are shown in the figure. The lower section is a modified differential and rear axle along with their respective housings from a small automobile. The lower differential side gear and shaft are restrained from turning by a rectangular beam pinned to the shaft. The "free" end of this beam rests on the outer face

of a fixed roller bearing. Four SR-4 type a-7 strain-gages are mounted on this beam and are so interconnected to form a strain-gage bridge for measuring the torque. The rotation of this lower shaft under load is in such a direction as to rotate the "free" end of the beam into the fixed roller bearing, which upon engagement with the beam, resists the torque.

The upper rear axle mates with the middle section by means of a splined coupling. This second section consists of a ball bearing supported shaft and housing. The third section is not shown but is identical with the second section.

The fourth section consists of the rotor hub, the strain-gage beams, and space for the incorporation of both cyclic and collective blade pitch controls if required later. A cross-sectional view is shown in figure 2. As may be seen from this figure, the rotor hub is keyed to the shaft and is driven through a ball-bearing slip-joint and universal joint. It is independently supported by two ball-bearings which are seated in the thrust-moment spider. A cross-sectional view of this spider is shown in figure 3. Four SR-4 type a-7 strain-gages are mounted on each arm of the spider, two on the top and two on the bottom. One of each pair of gages on each arm are so interconnected as to measure the thrust and cancel out the moments. The rolling and pitching moments are measured by interconnecting the remaining gages on opposite arms in such a manner as to cancel out the thrust in each circuit.

The thrust-moment spider is supported by the side and drag force strain-gage beams. A ball and socket joint is used for the connection. In order that the rotor hub would have a relatively stiff support, it was necessary to design the horizontal force beams to have a bending stiffness that was not commensurable with the strains to be measured. To alleviate this problem, the beam was made

considerably thicker than required and then slitted as indicated in figure 2 to give the proper strength but place the strain gages at a suitable distance from the neutral plane of the beam. An SR-4 type a-7 strain gage was mounted on the slitted sides of each of four beams and the gages on opposite beams were interconnected in a similar manner as the moment gages. A total number of twenty-eight gages were used to measure the six-components: eight gages for the thrust and four each for the torque, rolling moment, pitching moment, side force and drag force. The gages were connected in a bridge type circuit and were temperature compensated. All measurements were recorded by an oscillograph.

Although all six-components were instrumented, only the thrust, torque, and horizontal force were measured in the tests described herein. It is estimated that depending upon the sensitivity of the galvanometer used in the oscillograph, the thrust could be read within ± 0.5 lb.; the torque within ± 0.08 ft. lb.; the drag force within ± 0.2 lb. For the direct reading SR-4 control box, the thrust could be read within ± 0.1 lb.; the torque within ± 0.03 ft. lb.

The presently used rotor hub has been designed for a two-bladed flapping rotor with off set flapping hinges. By redesigning the hub, any conventional rotor system may be statically tested. It is also to be noted that the support structure has been kept small and compact for possible use in wind tunnels.

When rotor blades only are to be tested, the rotor hub will be driven through the differential by an electric motor.

Test Procedure:

The tests conducted were relatively simple. The model was run at normal rotor speed and the collective blade pitch angle was reduced until the thrust

was zero. The blades were checked for tracking and the rotor stopped. The blade pitch angles were then calibrated. The rotor was started again and beginning at zero blade pitch, 935 RPM, steady state data were taken at approximately 2° intervals and constant rotor speed until the blades began to stall. The collective blade pitch angle was then reduced in approximately 2° intervals and constant speed until zero thrust was again reached. The same run with the exception of zero thrust was repeated at a rotor speed of 1155 RPM. Constant rotor speed was maintained within 2% by use of a strobotac-strobolux. Thrust, torque, blade pitch angle, and rotor RPM were recorded.

For the second group of tests, the rotor was run at several different collective blade pitch angles and rotor speeds. In each condition, several values of cyclic blade pitch angles were introduced. The resultant rotor tilt angles and horizontal forces were recorded as well as the thrust, torque, collective and cyclic blade pitch angles, and rotor speed.

Test Results and Discussion:

The test results are presented in figures 4 and 5 and were obtained from a direct reading SR-4 control box. Figure 4 is a plot of thrust coefficient, C_T versus collective blade pitch angle, θ_o and a comparison with the theory presented in the appendix of reference 2. As may be seen from the figure, the theory and experimental data compare very well. The slope of the lift curve used in the theory was obtained from reference 3 from data on a NACA 0015 airfoil of infinite aspect ratio, and the approximate Reynolds number corresponding to the blade three-quarter-radius station. The value used was 5.53 per radian for a Reynolds number of 340,000.

Figure 5 is a plot of torque coefficient, C_Q, versus thrust coefficient, C_T, and a comparison with the theory of reference 2. As may be seen, the theory and experimental data also compare very well. However, in order to accurately predict the torque coefficient, it is necessary to express the local profile-drag coefficient as a function of the local lift coefficient. It was found that by making the approximation that

$$c_{d_o} = 0.0102 + 0.70\left(\frac{c_l}{a}\right)^2$$

the theory could accurately predict the experimental data. In order to indicate the degree of approximation involved, this curve is plotted in figure 6 along with the infinite aspect ratio characteristics of the airfoil section as obtained from reference 3. As may be seen, a very close approximation of the variation of the profile drag coefficient with lift coefficient is obtained.

The lack of scatter in the data of figures 4 and 5 and the lack of any noticeable hysteresis is pointed out as an indication of the satisfactory operation of the thrust and torque measuring equipment.

The steady state, zero air speed results of introducing a cyclic blade pitch angle are well known and the model did not deviate from the expected pattern. The rotor flapping angle with respect to the shaft was indentical within experimental error to the cyclic blade pitch angle introduced and the thrust vector remained perpendicular to the tip-path plane. These tests were made as a further validation of the instrumentation. This data was considered somewhat superfluous and is not included in the report.

Although, all traces indicated vibratory forces or moments at rotor harmonic frequencies, there was no indication of anything new that could not be explained from geometric considerations.

It was not possible to measure the transient rotor flapping angles accurately enough at this time due to instrumentation difficulties. For this reason, the desired stability derivatives were not obtained.

Conclusions:

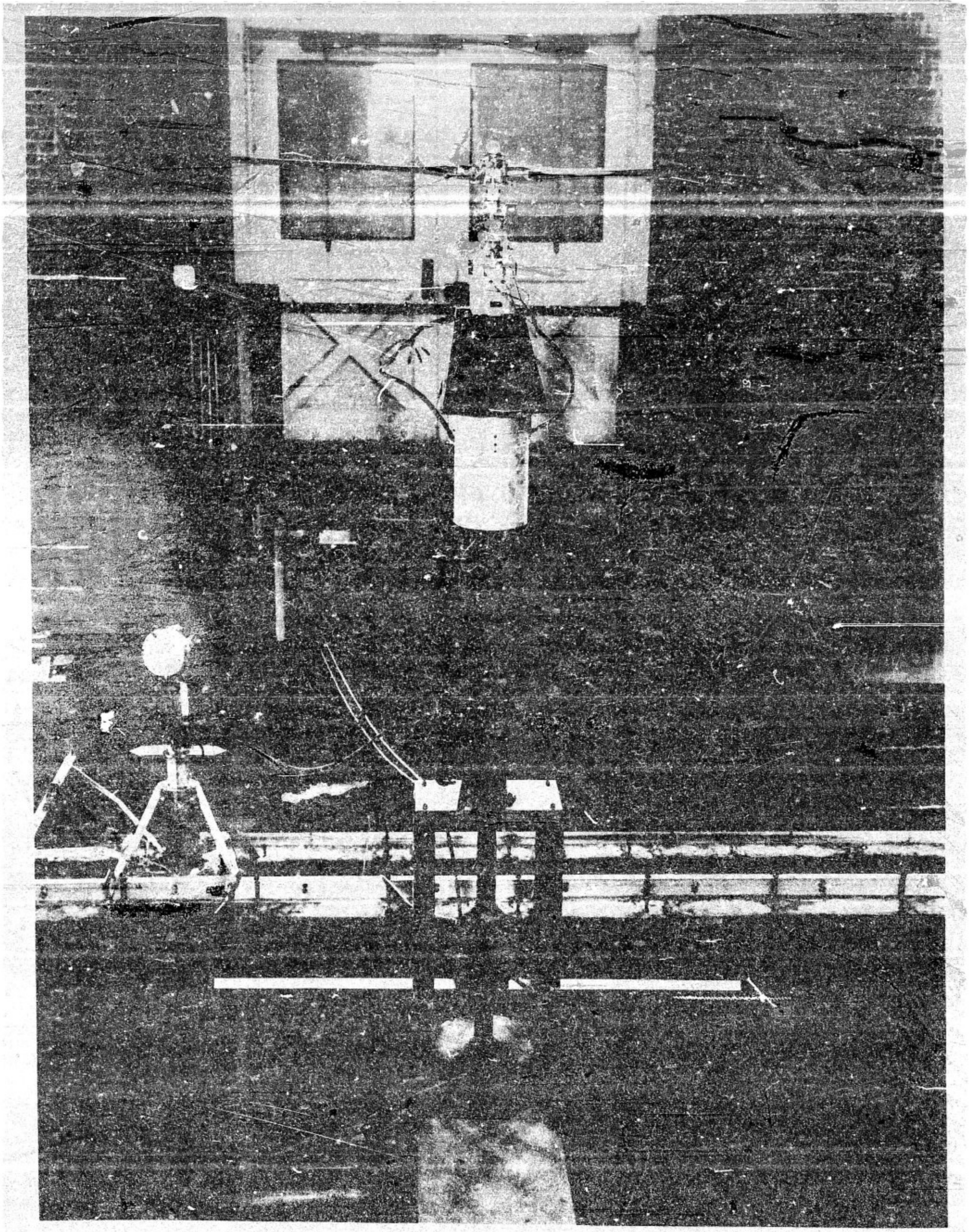
A six-component strain-gage model rotor test stand has been developed and applied to the static thrust analysis of a helicopter model having a six-foot diameter two-bladed teetering rotor. From these tests it is concluded that the rotor test stand yields accurate and repeatable results.

References:

1. Gray, R., McCaskill, A., Gebhard, D., and Goland, L., "Model Study of Helicopter Dynamic Stability and Control, Phase II. Comparison of Theoretical and Experimental Results Near Hovering Flight," Princeton University Aero. Eng. Dept. Report No. 230, May, 1953.

2. Castles, Walter and Gray, Robin, "Empirical Relation Between Induced Velocity, Thrust, and Rate of Descent of a Helicopter Rotor as Determined by Wind-Tunnel Tests on Four Model Rotors," NACA TN 2474, 1951.

3. Jacobs, Eastman N. and Sherman, Albert, "Airfoil Section Characteristics as Affected by Variation of the Reynolds Number," NACA TR 586, 1937.



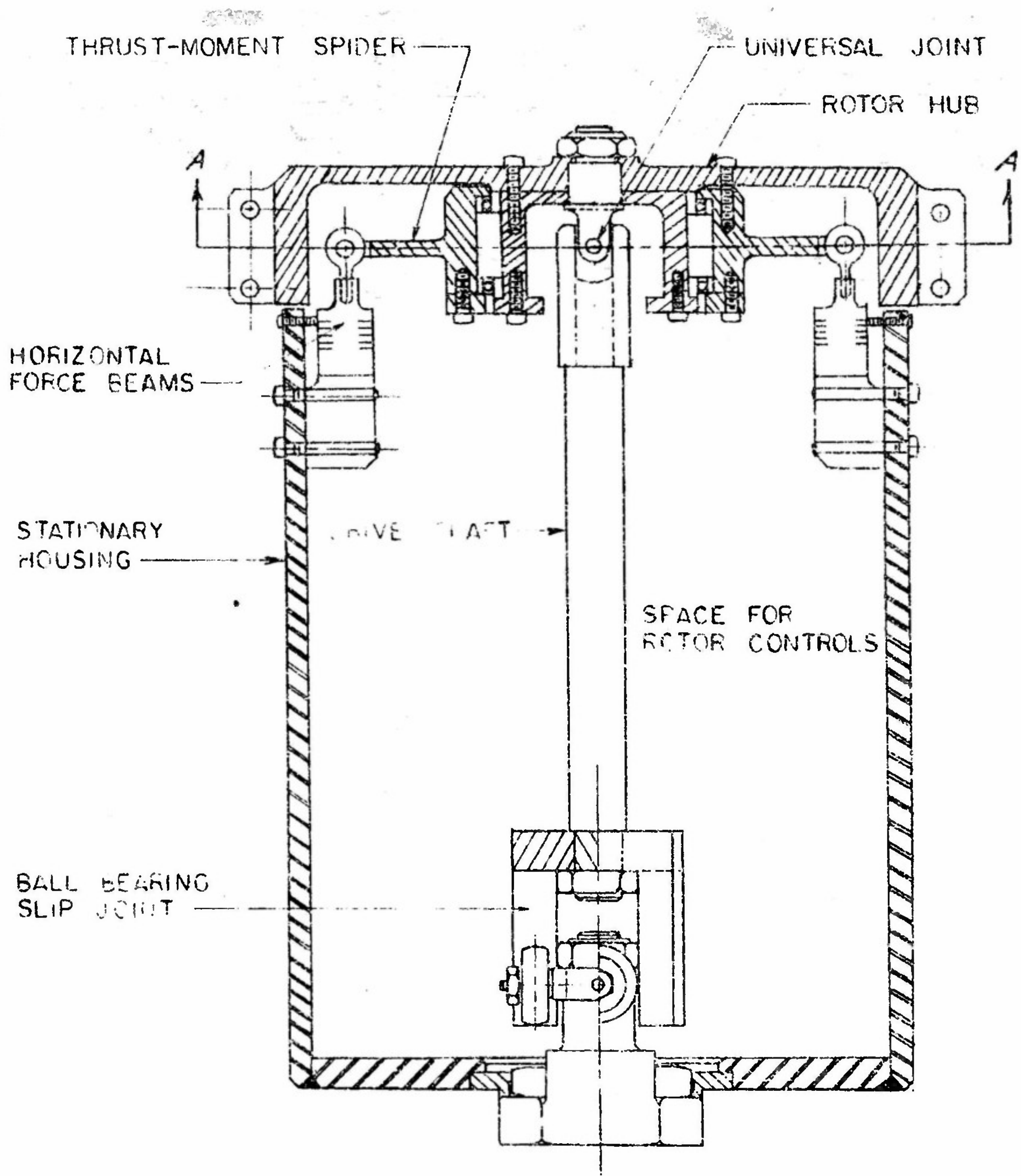


FIGURE 2. SECTION VIEW OF ROTOR HUB AND STRAIN GAGE BEAMS.

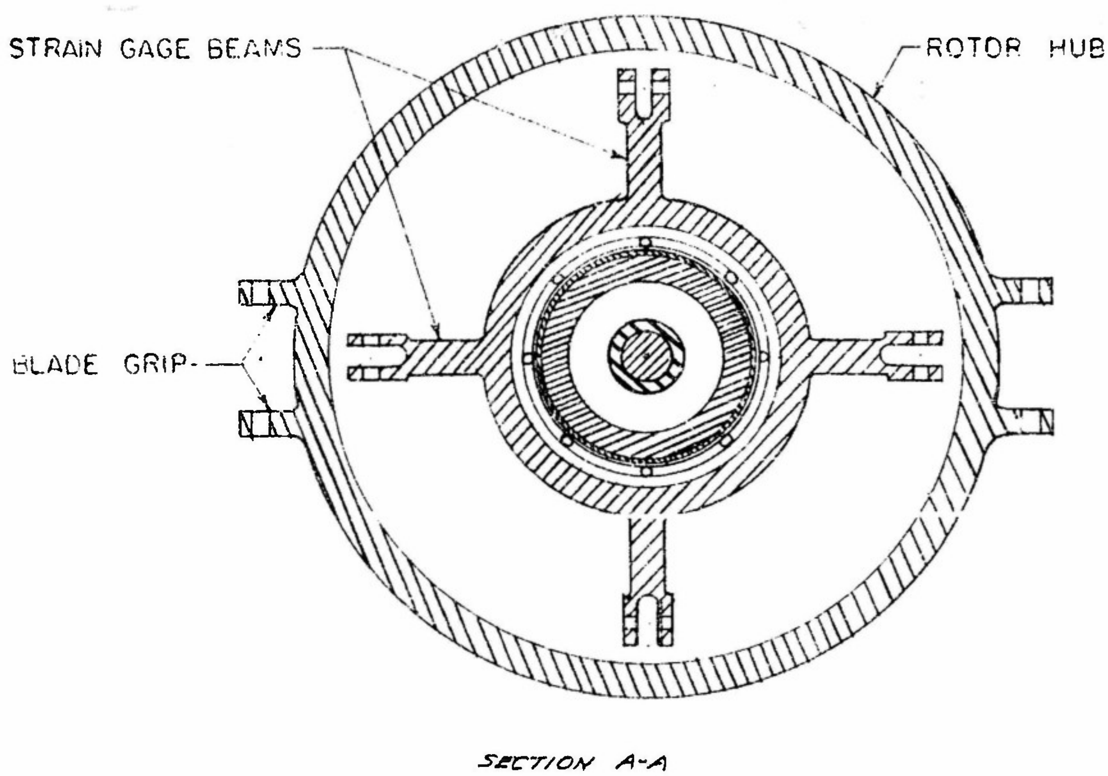


FIGURE 3. PLANVIEW OF THRUST-MOMENT STRAIN GAGE SPIDER.

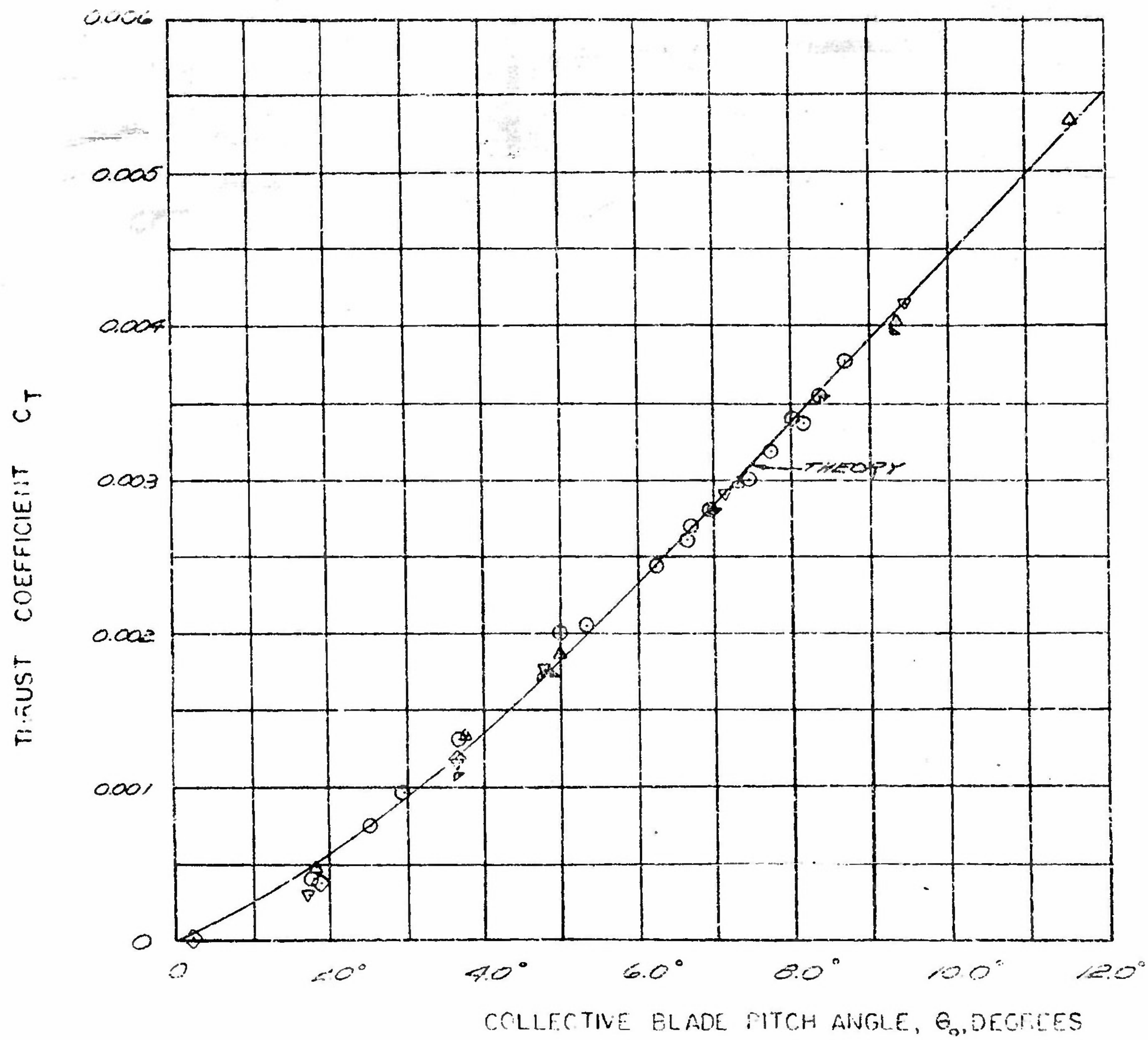


FIGURE 4. ROTOR TEST STAND DATA. THRUST COEFFICIENT VERSUS BLADE PITCH ANGLE AND A COMPARISON WITH THEORY.

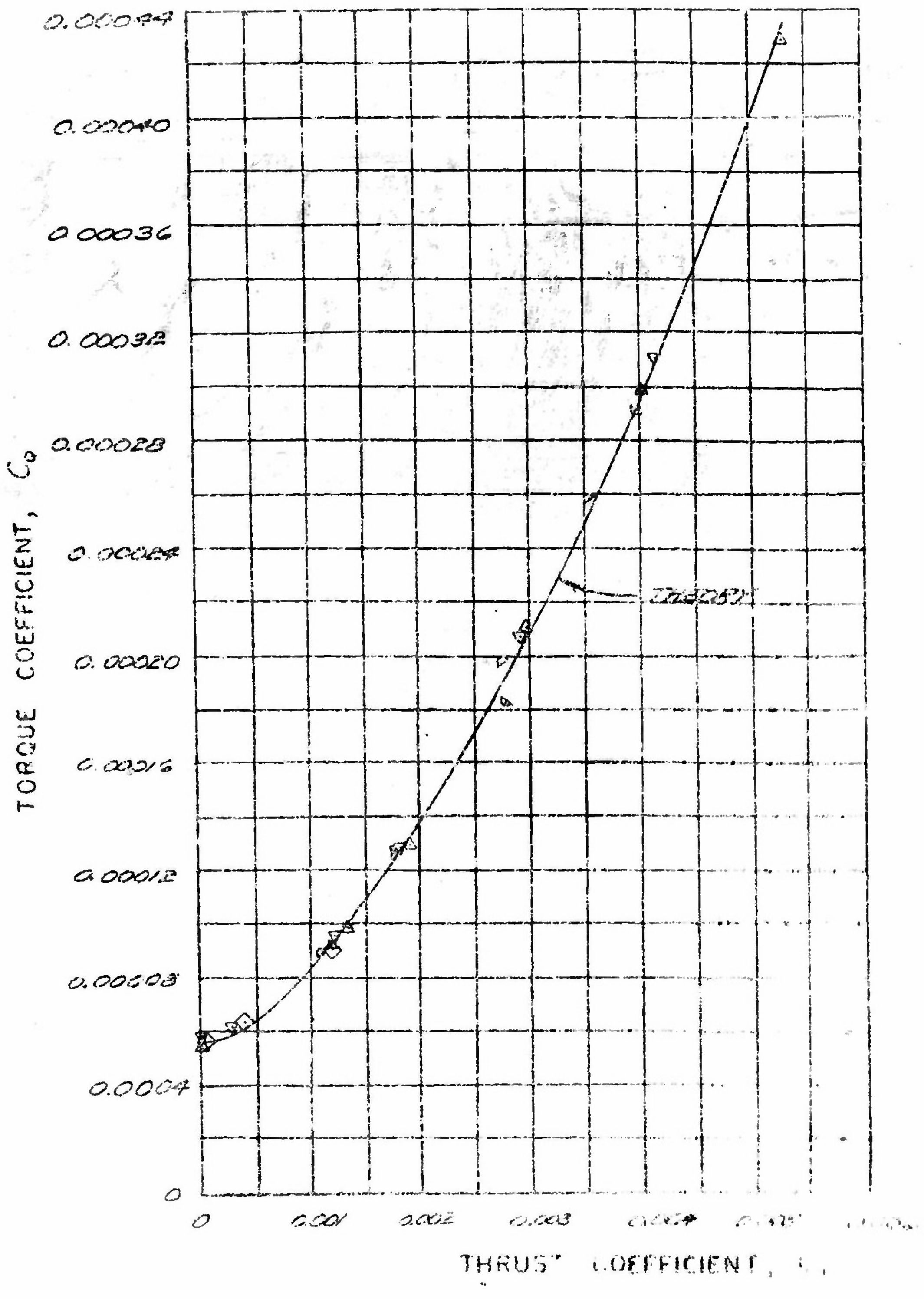


FIGURE 5. ROTOR TEST STAND DATA. TORQUE COEFFICIENT VERSUS THRUST COEFFICIENT AND A COMPARISON WITH THEORY.

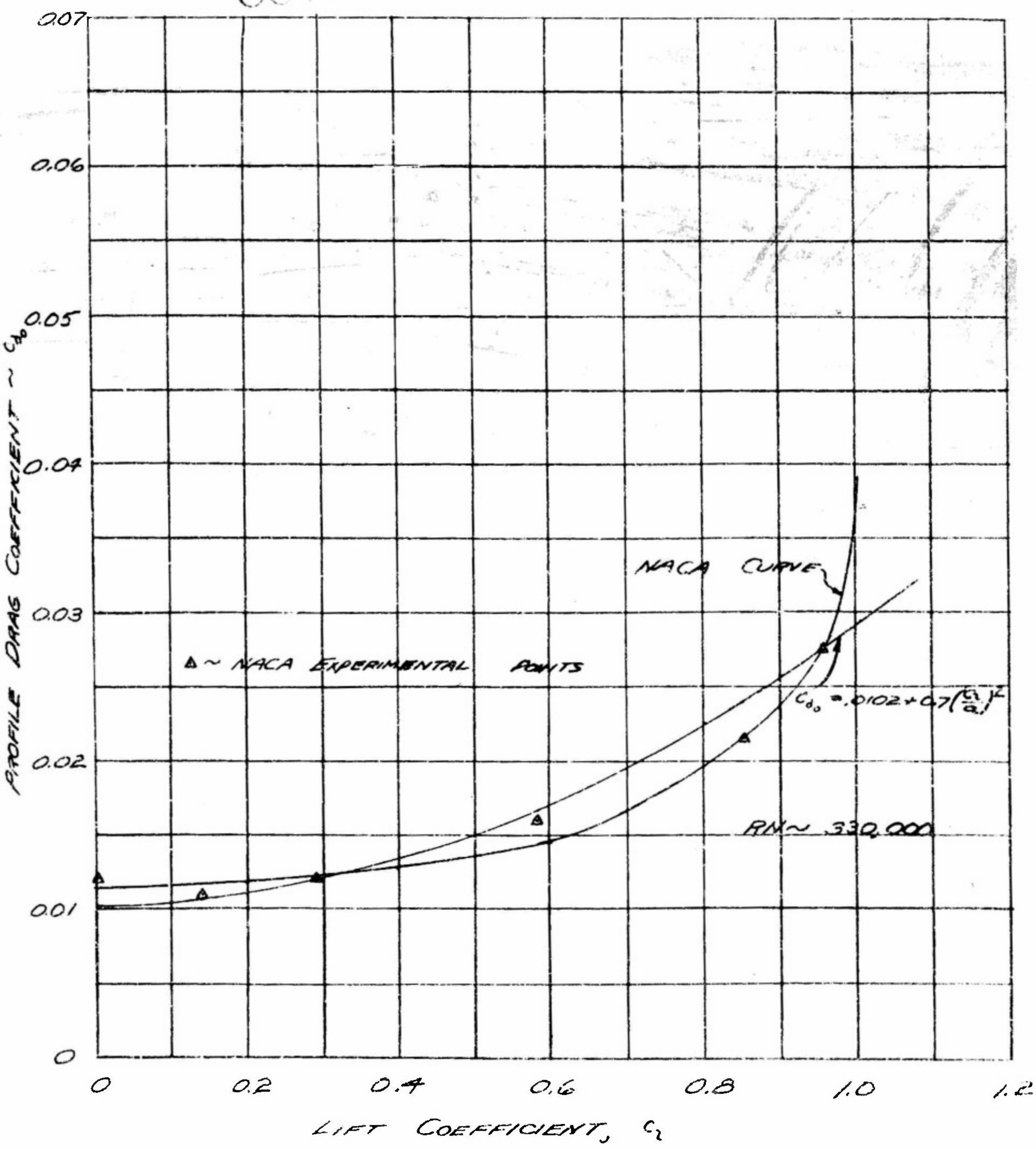


FIGURE 6. COMPARISON OF ROTOR TEST STAND AIRFOIL SECTION CHARACTERISTICS WITH TWO DIMENSIONAL CHARACTERISTICS.